



# Deployable Landing Leg Concept for Crew Exploration Vehicle

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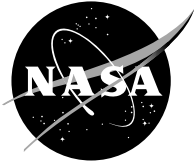
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# **Deployable Landing Leg Concept for Crew Exploration Vehicle**

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## **Abstract**

The NASA Exploration program is investigating the merits of land landing concepts for the Crew Exploration Vehicle (CEV). Four options are under investigation: retro-rockets which fire and slow the vehicle before contact with the landing surface, deployable crushable material which deploys just before landing and crushes during land contact, airbags which deploy just before landing and deflate during land contact, and deployable legs which deploy before landing and contain material that absorbs energy during land contact. The purpose of the present work is to determine the effectiveness of the deployable leg concept. To accomplish this goal, structural models of the deployable leg concept are integrated with the Crew Module (CM) and computational simulations are performed to determine vehicle and component loadings and acceleration levels. Details of the modeling approach, deployable leg design, and resulting accelerations are provided.

## **Introduction**

The NASA Exploration program is investigating the merits of water and land landings for the Crew Exploration Vehicle (CEV). The merits of these two options are being studied in terms of cost and risk to the astronauts, support personnel, and general public. For land landings, four options are under investigation: retro-rockets which fire and slow the vehicle before contact with the landing surface, deployable crushable material which deploys just before landing and crushes during land contact, airbags which deploy just before landing and deflate during land contact, and deployable legs which deploy before landing and contain material that absorbs energy during land contact. All four of these concepts, as well as water landing, employ parachutes to slow the vehicle to acceptable landing velocities. The purpose of the present work is to determine the effectiveness of the deployable leg concept. To accomplish this goal, structural models of the deployable leg concept are integrated with the Crew Module (CM) and computational simulations are performed to determine vehicle and component loadings and acceleration levels. Details of the modeling approach, deployable leg design, and resulting accelerations are provided.

Ideally, a detailed structural model of the Crew Module and an accurate model of the landing medium (i.e., soil, rocks, and trees) would be used to simulate each of the land landing scenarios. The detailed model of the vehicle would include the elastic and nonlinear behavior of all the structural components including the contribution of damping and energy-absorbing components such as crushable materials on the bottom of the vehicle outer shell and shock absorbers used to mount the pallet where the astronaut seats are mounted. Additionally, the model would include any landing attenuation system such as the deployable legs. This model would be capable of accurately predicting transient accelerations throughout the vehicle in addition to crew member body accelerations. The model would also be able to predict stress levels in different components throughout the vehicle structure. The model of the landing medium would fully characterize the actual landing soil and terrain behavior including the actual deformation of the soil and the soil's contribution to absorbing energy from the incoming vehicle both in the vertical and horizontal directions. For the present study however, a simplified structural model of the vehicle and landing surface is employed. A simplified model is used since at the time of this study, a higher fidelity model is not available, nor would it have been practical to perform a high level of simulation fidelity with all of the possible landing conditions since specific landing conditions have not been defined. The

simplified model consists of a rigid structural model of the vehicle with the landing legs modeled as energy-absorbing mechanical components. The landing medium is modeled as a simple elastic, plastic material with energy-absorbing behavior. Further details of the model are provided later in this report.

Before proceeding with a discussion of the Crew Module vehicle model and landing results, it is necessary to point out a fundamental constraint behind vehicle landings. The constraint is, regardless of the design or configuration of the landing vehicle, the vehicle will require a minimum stopping distance in which it must slow down without exceeding a specified acceleration limit. For retro-rockets, this distance is measured from the point of the initial rocket firing to the point where the vehicle comes to a stop. For the other landing attenuation concepts, the distance is measured from the point where the attenuation system first incurs loading and begins absorbing energy to the point where the vehicle stops moving. The point to emphasize is that acceleration limits equate directly to a minimum stopping distance regardless of the vehicle design and attenuation system employed. If the vehicle needs, for example, 12 in. of space to decelerate from some initial velocity, it will need this space regardless of whether airbags, deployable legs, or crushable material is used.

Figure 1 depicts the required stopping distance for limiting accelerations to astronauts aboard the CEV. The curves in this figure are computed using simple basic principles of physics for the relationships between acceleration, velocity, and displacement. Using these relationships, the resulting acceleration is computed from the maximum available displacement that the Crew Module has to decelerate from an initial landing velocity to a stationary resting position. As expected, the curves in the figure show that the acceleration levels increase as the landing velocity increases. Conversely, as the distance that the capsule has to come to a complete rest is increased, the resulting acceleration decreases.

The available distance for the capsule to come to rest is affected by a combination of the compliance of the landing medium (e.g., soil), the elasticity of the capsule, and any shock-absorbing material and/or attenuation mechanisms that may be part of the capsule design. These curves represent best case scenarios, and careful design of the Crew Module will be required to attain these levels of accelerations. Furthermore, any acceleration attenuation mechanisms that are provided as part of the capsule will require at least as much displacement as is depicted in the figure.

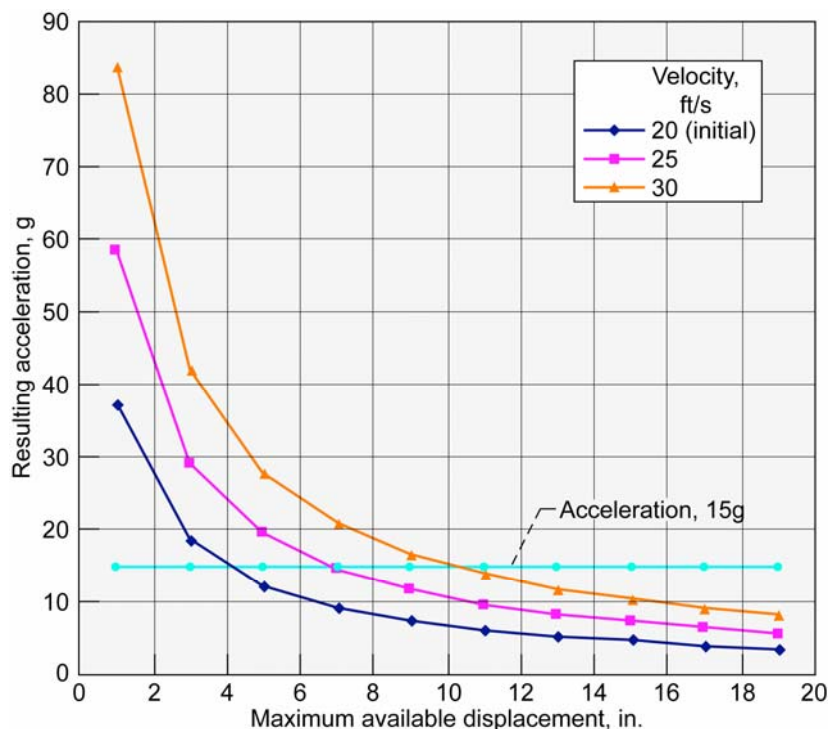


Figure 1.—Best-case scenario for acceleration.

## Crew Exploration Vehicle Model

The finite element program, LS-DYNA is used to perform the analysis of the deployable leg concept. This commercially available program is selected because of its ability to simulate the complex transient dynamic behavior of the Crew Module with attached deployable legs impacting a landing surface (fig. 2). The individual parts and their specific properties for the deployable leg Crew Module model are listed in table I. The main portion of the vehicle, which consists of the pressure vessel, associated structure, and internal components, is modeled as a rigid part having inertia properties equivalent to the DAC-II Crew Module design (table II). Since this part is modeled as rigid, it will act as a rigid mass, it will exhibit no structural deformation, and no structural loadings will be computed for it. Figure 2 depicts the Crew Module with deployable leg attenuation system. Notice that the top portion of the pressure vessel is missing. This does not affect the simulation results since the full inertia effects of the vessel are included; however it does reduce the number of elements and the computational effort required for the simulations.

TABLE I.—DEPLOYABLE LEG CEV CONCEPT PART LIST

Part no.	Part description
2	Pressure vessel and stiffeners (rigid inertia)
3	Landing feet (elastic plates)
4	Support ring (elastic beams)
8	Secondary shock absorbers—rear (inelastic discrete spring—tension only—mat S8)
9	Primary shock absorbers—outer shell (stiff beam—elastic bending—no axial stiff)
10	Short stubs (soft elastic bending)
15	Rigid soil
18	Secondary shock absorbers—rear (inelastic discrete spring—compression only—mat S8)
19	Primary shock absorbers—inner core—rear (inelastic axial discrete spring—compression only—mat S8)
29	Primary shock absorbers—outer shell (stiff beam—elastic bending—axially stiff)
31	Secondary shock absorbers—front (inelastic discrete spring—tension only—mat S8)
32	Secondary shock absorbers—front (inelastic discrete spring—compression only—mat S8)
33	Primary shock absorbers—inner core—front (inelastic axial discrete spring—compression only—mat S8)

TABLE II.—CEV PROPERTIES

Mass, lbm (lb)	32.608 (12,600)
Ixx, lbm/in. <sup>2</sup>	101,904
Ixy, lbm/in. <sup>2</sup>	3296.9
Ixz, lbm/in. <sup>2</sup>	-4196
Iyy, lbm/in. <sup>2</sup>	79,725.6
Iyz, lbm/in. <sup>2</sup>	0
Izz, lbm/in. <sup>2</sup>	73,731.2
Rigid spacecraft (MAT_RIGID)	
CG <sup>1</sup> at (134, 0, -11.5) from the theoretical CM <sup>2</sup> Apex (positive X from apex to heat shield, positive Z from feet to head, RHR <sup>3</sup> denotes Y)	

<sup>1</sup>center-of-gravity

<sup>2</sup>crew model

<sup>3</sup>right-hand rule

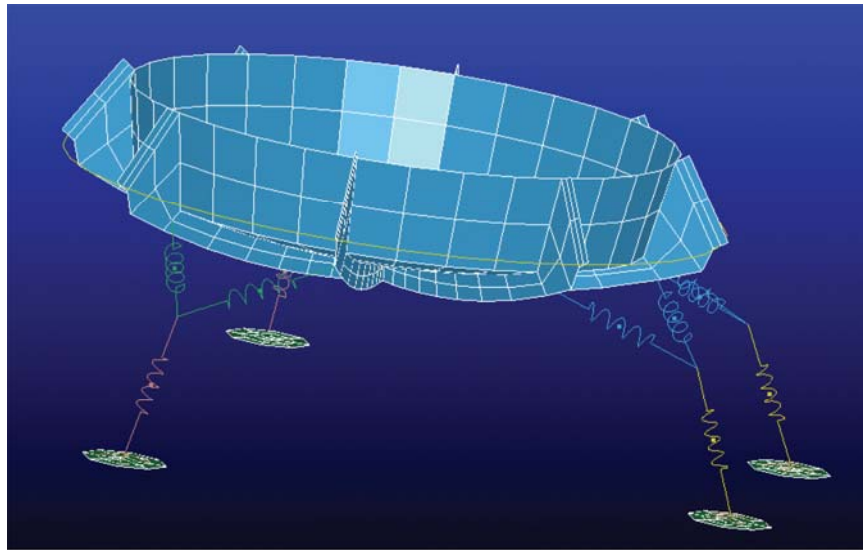


Figure 2.—Crew Exploration Vehicle (CEV) deployable leg model.

The landing surface, like the pressure vessel, is also modeled as a rigid part. In reality the landing surface will be some form of soil that will deform on impact and absorb energy. However, for the purpose of the present study the landing surface is assumed to not deform, and, thus absorb no energy resulting from landing. (This will lead to more conservative results than will be reported here.) The landing surface is made large enough so that the vehicle will not leave the surface during the range of landing simulations that are performed in this study. Since the landing surface is both smooth and rigid, the effect of surface irregularities and soil movement are not included in the simulations.

The primary and secondary landing leg designs are fundamentally similar to the design of the landing legs used for the Apollo Lunar Module (fig. 3). The primary legs connect the landing pads to the vessel and act primarily in compression, while the secondary legs brace the primary legs to the vessel and act in both compression and tension, depending on the landing conditions. Similar to the Lunar Module, the primary landing legs are designed for compression only while the secondary legs are designed for both compression and tension. Both the primary and secondary landing legs are constructed of an outer housing that contains a crushable material. The crushable material is designed to provide a constant force regardless of the leg displacement. The constant force behavior is optimal for providing a constant deceleration to the vehicle, because with proper design of the crushable material, the constant force is tailored to maintain acceleration levels at or below design criteria. A limitation of the crushable material and its associated constant force characteristics is that the material can only be designed for a single design condition and performance at off-design conditions will therefore be less than optimal.

The deployable legs are modeled using several parts (fig. 4). For the primary landing legs, the upper section (above the secondary strut attachment point) is modeled with a beam element that carries bending and axial loads. The top of the beam is attached to the Crew Module pressure vessel with a pinned connection. The lower end of the beam is attached to a second beam element that carries bending loads but has no axial stiffness. Parallel to this lower beam section is a discrete (one-dimensional) element that carries the axial load and is characterized with a nonlinear material property representative of the crushable material.

The lower end of the primary struts are attached to landing feet that are pinned to the lower legs and provide the contact surface between the Crew Module and landing surface. Since the primary legs carry bending loads and are pinned to the pressure vessel, any off-axis loading is fully transmitted to the secondary landing legs which are modeled entirely as discrete elements possessing material properties. Similar to the primary leg discrete elements, the secondary landing legs behave as crushable material. In effect, both the primary and secondary legs are able to absorb landing energy and are used to minimize the accelerations incurred on the vehicle during landing.



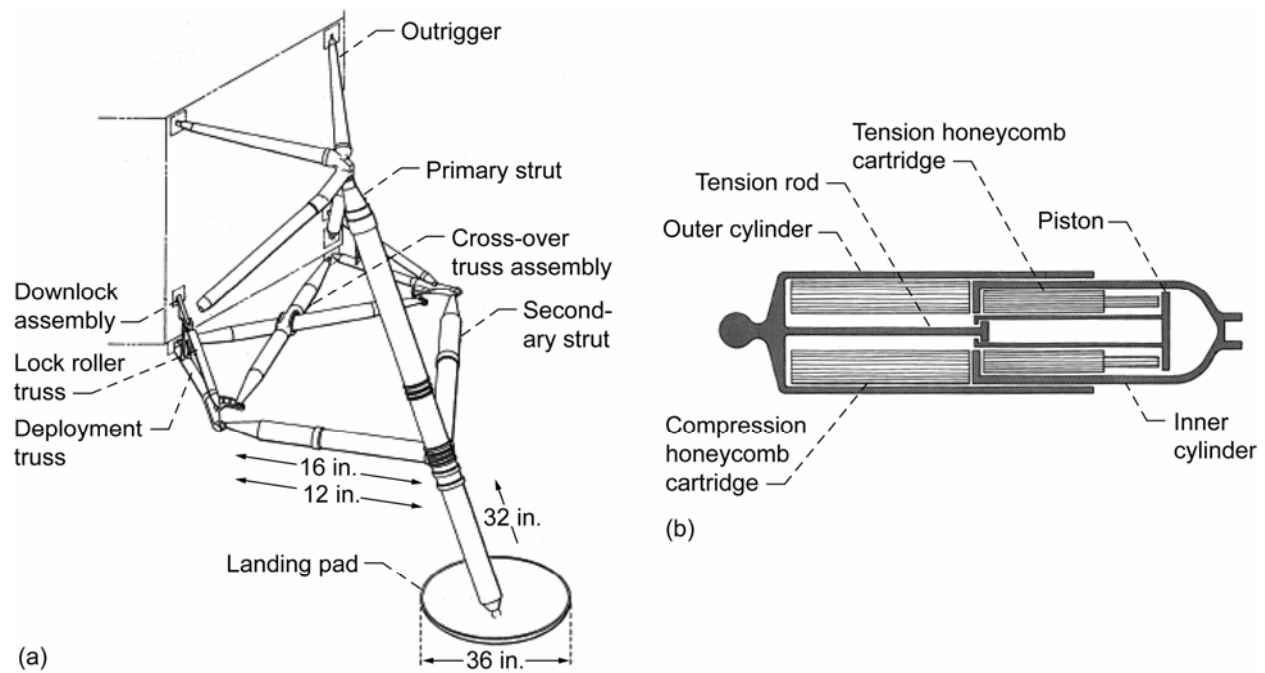


Figure 3.—Apollo lunar landing gear. (a) Strut configuration. (b) Secondary strut.

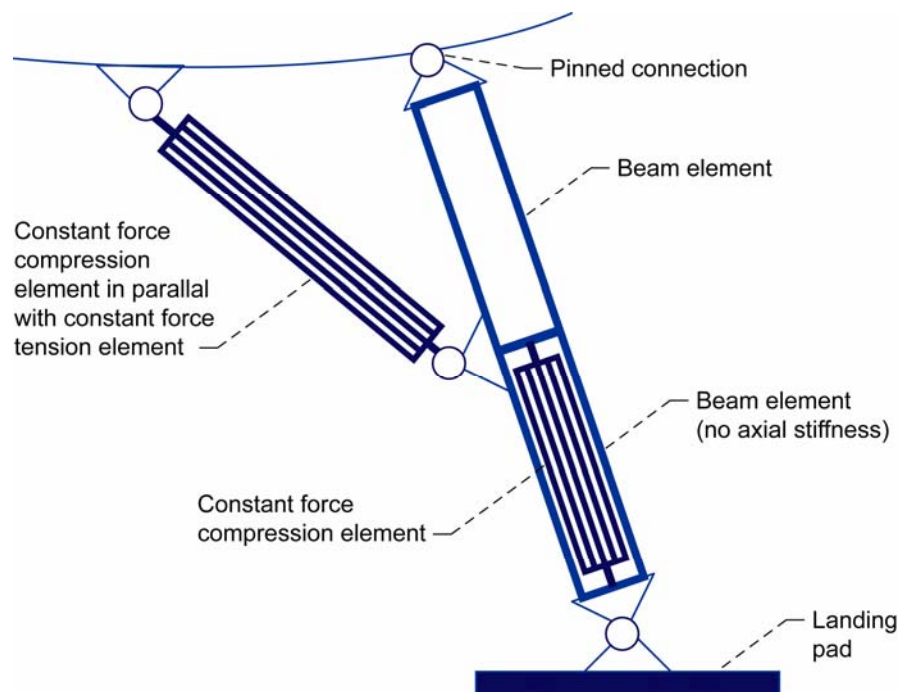


Figure 4.—Deployable leg modeling strategy.

## Deployable Leg Design

Several design iterations are evaluated before an acceptable design is identified (table III). Engineering judgment was used for each iteration which then led to a final acceptable design. However, a more optimal design may be found through the use of a more rigorous design approach such as design optimization. There are several design variables that could be altered to reach an optimal design. The length of the legs, the crushable force, and the stroke length could all be modified in an attempt to reach the best design. Additionally, the crushing force profile could be designed to vary with stroke length. A variable crushing force could be beneficial since it has been found that the human body can tolerate larger accelerations, thereby reducing stroking requirements so long as they are for very short durations.

TABLE III.—DEPLOYABLE LEG DESIGN

Design iteration	Front legs		Rear legs	
	Secondary legs	Primary legs	Secondary legs	Primary legs
1	Fc = 20,000 lb 17-in. stroke	Fc = 20,000 lb 17-in. stroke	Fc = 35,000 lb 17-in. stroke	Fc = 30,000 lb 17-in. stroke
2	Fc = 20,000 lb 17-in. stroke	Fc = 30,000 lb 17-in. stroke	Fc = 50,000 lb 17-in. stroke	Fc = 25,000 lb 17-in. stroke
3	Fc = 20,000 lb 17-in. stroke	Fc = 40,000 lb 30-in. stroke	Fc = 50,000 lb 17-in. stroke	Fc = 20,000 lb 17-in. stroke
4	Fc = 20,000 lb 17-in. stroke	Fc = 30,000 lb 17-in. stroke Add spring—K = 30,000/17	Fc = 50,000 lb 17-in. stroke	Fc = 50,000 lb 17-in. stroke Add spring—K = 50,000/17

For the first design iteration, it is assumed that a landing with a vertical velocity only would drive the design. For this condition one can see that the rear legs would take more load than the front legs due to their geometric location, so the crushable strength of the rear legs is made stiffer than the front legs. Both the front and rear primary and secondary legs are given the same crushing properties, and a stroke length of 17 in. (based on geometric constraints) is provided. In actuality, the primary legs tend to stroke closer to 17 in., while the secondary legs typically undergo only a few inches of travel. The results of this first design are acceptable for vertical-only landings, but when horizontal velocities are introduced, the rear legs tend to collapse and the vehicle bottoms out on the landing surface because of the rear secondary legs' lack of strength.

The second design iteration takes into account horizontal velocities and tries to address the issues of the rear leg collapse. Several things are modified in this iteration. First, the rear secondary leg crushing strength is increased to prevent collapse during large horizontal landing velocities. Second, the front primary legs are slightly strengthened for horizontal landings, and finally, the rear primary legs are slightly softened to try and neutralize the stiffening of the other legs. This design configuration performed much better than the first design, however the front legs bottomed out during large horizontal landings, and the rear legs still had extra load capacity in that only a fraction of their crushable load capacity was reached.

The third design iteration is very close to the second design except that it has slightly stiffer front primary legs and slightly softer rear primary legs. This design appeared to work very well except that for larger horizontal landing velocity cases and for cases that had a nonzero pitch landing angle, the primary landing legs would exceed their 17 in. of travel and bottom out. At this point all the flexibility in the analysis model is used up, and only rigid body behavior is left in the model, therefore very large accelerations are predicted by the model. In reality, a "real" vehicle would have inherent flexibility and the ability to attenuate loadings, and since the vehicle had actually slowed to reasonable velocities, large accelerations would not actually be realized.

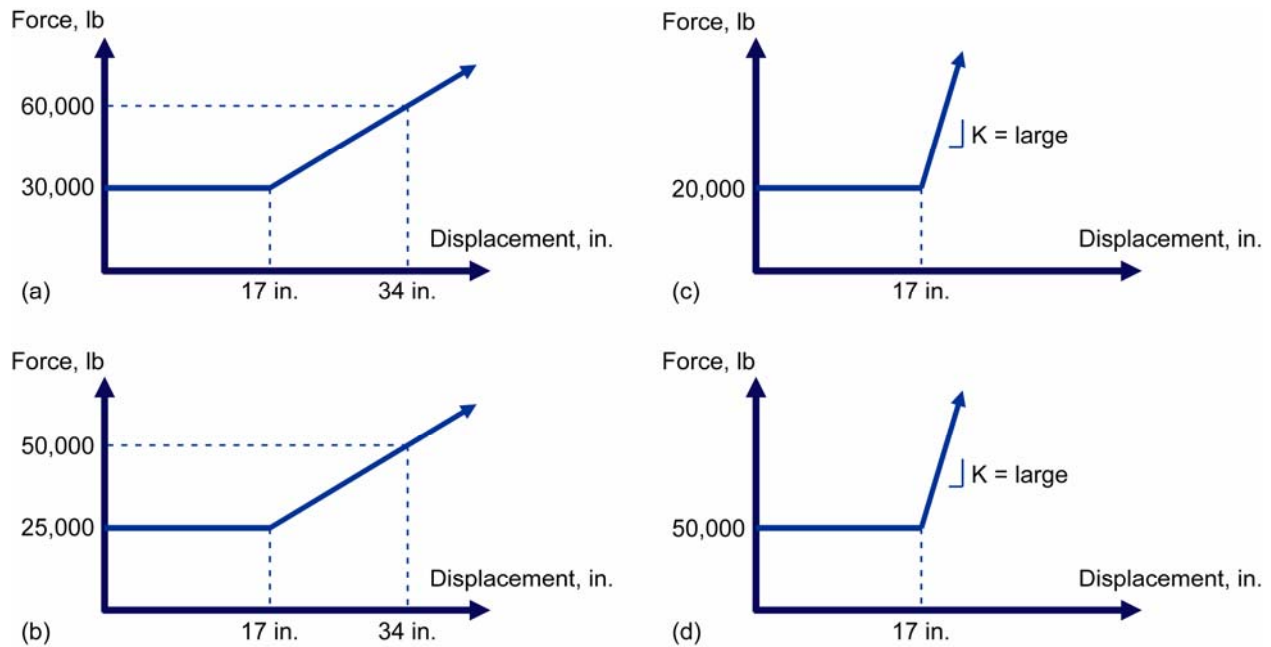


Figure 5.—Deployable leg properties. (a) Primary legs—front. (b) Primary—rear. (c) Secondary—front. (d) Secondary—rear.

The fourth design iteration is identical to the third design except that instead of the legs bottoming out when their stroke limit is reached, a linear spring with stiffness equal to twice the crushing strength is added to each primary leg (fig. 5). These springs do not absorb any energy, but they serve to reduce the large accelerations that occur in the previous design when the legs bottom out. For an actual design some sort of bottoming spring may be required, or the flexibility of the vehicle and landing surface itself may provide enough attenuation that bottoming springs are not even required. The results presented subsequently in this report are generated using the fourth design and its associated properties.

## Simulation Results

Simulation results are generated for a variety of load cases (fig. 6). The load cases are selected to encompass a wide enough range of landing conditions such that a complete assessment of the deployable leg concept is provided. Furthermore, the identical simulation matrix is used for the other three landing concepts so that a comparison among all four concepts could be performed. The four landing variables are vertical and horizontal velocity, center-of-gravity (cg) orientation, and pitch angle. For the present study, cg orientation and vertical velocity are held constant and only horizontal velocity and pitch angle are varied. The results are reported in a body-fixed coordinate system that is fixed in the vehicle and rotates as the vehicle rotates (fig. 7). The axes of this body fixed system correspond to the directions that are used to assess injury risk levels to the astronauts. The body fixed x-axis, y-axis, and z-axis correspond to the eyes in/out, sideways, and spine directions of the astronauts in the vehicle. The use of these axes allows for the acceleration time histories to be directly input into the Brinkley model used to assess astronaut injury risk.

Vertical velocity, $V_v$ , ft/s	×	Horizontal velocity, $V_h$ , ft/s	×	Center of gravity orientation	×	Contact angle, deg
25		0		Forward (direction of $V_h$ ) +11.5 in.		-15
		20				0
		40				+15
		60				

Figure 6.—Land landing simulation matrix.

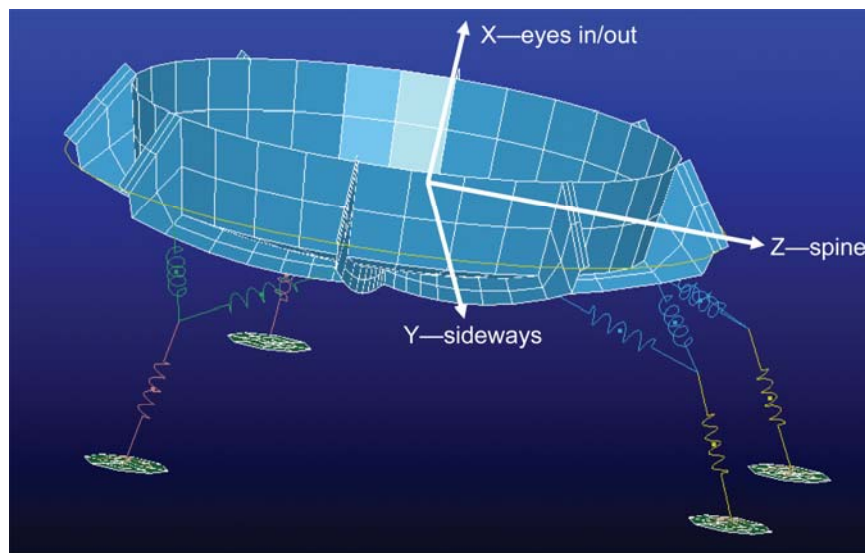


Figure 7.—Body fixed coordinate system.

The first load case run is for a vertical velocity of 25 fps, horizontal velocity of 0 fps and a zero pitch angle (fig. 8). For this load case the primary front and rear legs stroke approximately 13 and 7 in., respectively. The 17-in. available stroke in the primary legs is not completely used. The force in the front and rear primary legs is 30,000 and 25,000 lb, respectively. As expected, these force levels are equivalent to the crushable design force. The area under the force curves is indicative of the energy absorbed by the legs. The secondary legs displace considerably less than the primary legs. While most of the secondary legs displace less than 2.5 in., several of the legs only displace about an inch. The force in the secondary legs, as expected, is equal to their design crushable force. The maximum displacement of the vehicle cg is over 20 in. in the vertical direction. The relatively large displacement allows for ample space for the vehicle to slow down and maintain acceleration levels within acceptable levels. The maximum acceleration is in the vertical direction and is held to approximately 9g or less (fig. 9).

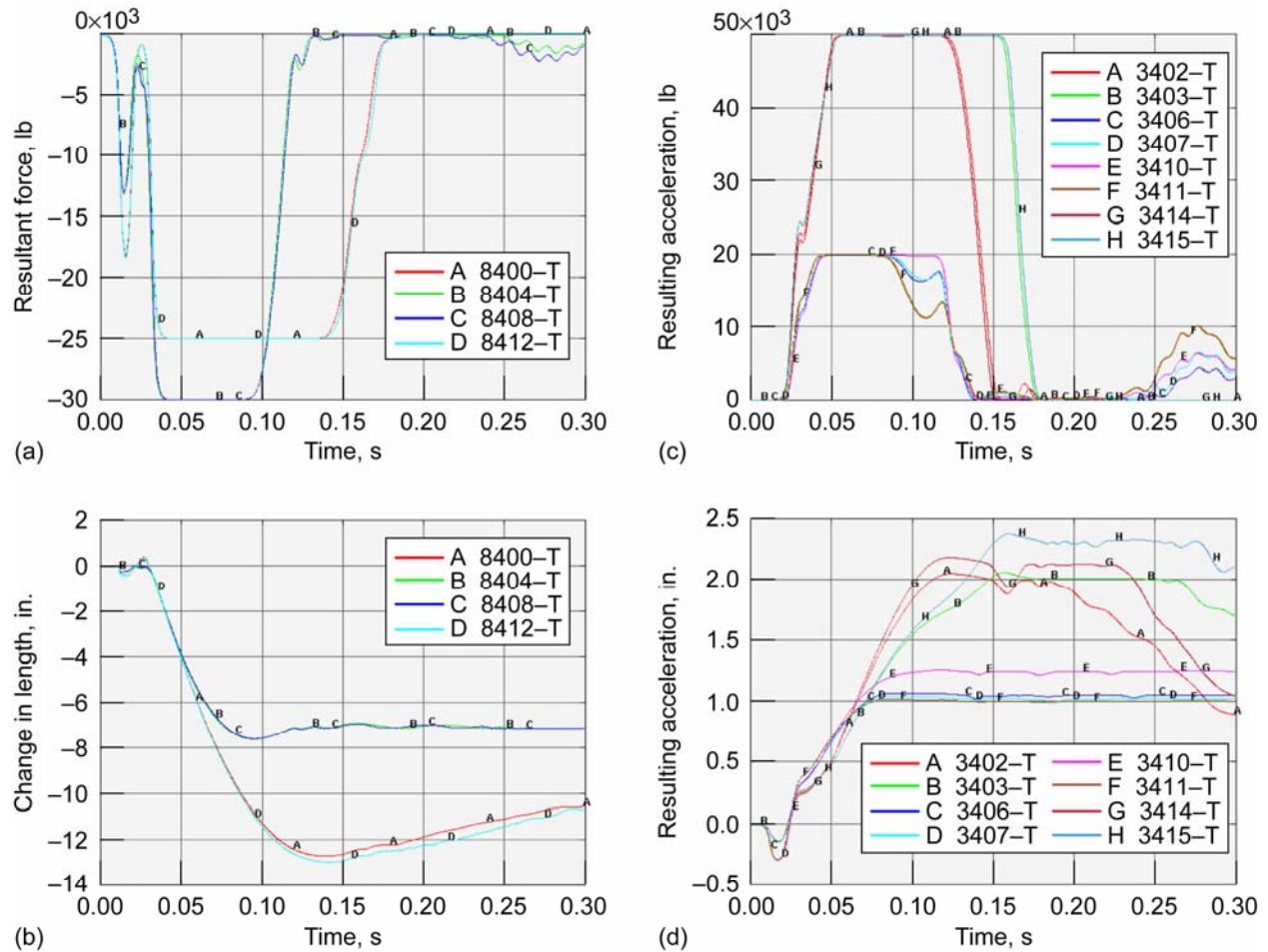


Figure 8.—Landing leg force and stroke. (a) Primary leg force. (b) Primary leg displacement. (c) Secondary leg force. (d) Secondary leg displacement. (Vertical velocity = 25 fps, pitch = 0 degrees, horizontal velocity = 0 fps).

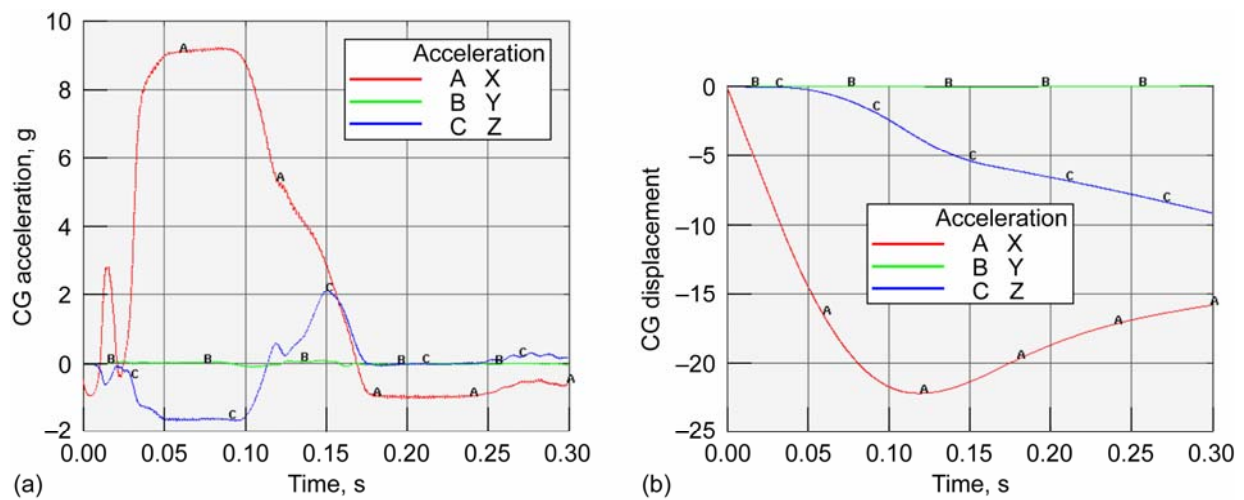


Figure 9.—CEV center-of-gravity motion. (a) Resulting acceleration, g. (b) Resulting acceleration, displacement. (Vertical velocity = 25 fps, pitch = 0 degrees, horizontal velocity = 0 fps).

Figures 10 through 20 show the resulting accelerations for each of the landing simulation cases. A summary showing the maximum accelerations in the x-axis, y-axis, and z-axis directions for each of the twelve load cases depicts the overall effectiveness of the deployable legs (table IV). In general, the maximum acceleration levels are fairly constant regardless of the loading conditions. For large horizontal landing velocities the maximum acceleration does not exceed 10g, while for zero horizontal landing velocity the maximum acceleration is 9g. Pitch angle also has limited effect on the resulting acceleration levels. For the nose down landing condition, the maximum acceleration is 10g while the maximum acceleration for the heel down condition is 9g. As mentioned previously in this report, the deployable leg design properties are tailored to accommodate the twelve landing conditions, and the results show the design is effective for all twelve cases.

TABLE IV.—SUMMARY OF MAXIMUM ACCELERATIONS<sup>a</sup>  
[Vertical velocity = 25 fps]

Horizontal velocity, fps	Pitch, degree		
	-15 (nose down)	0	+15 (heel down)
	Maximum acceleration, g		
0	4	9	8
20	8	8	7
40	8	8	9
60	10	8	6

<sup>a</sup>maximum of X, Y, or Z body fixed direction.

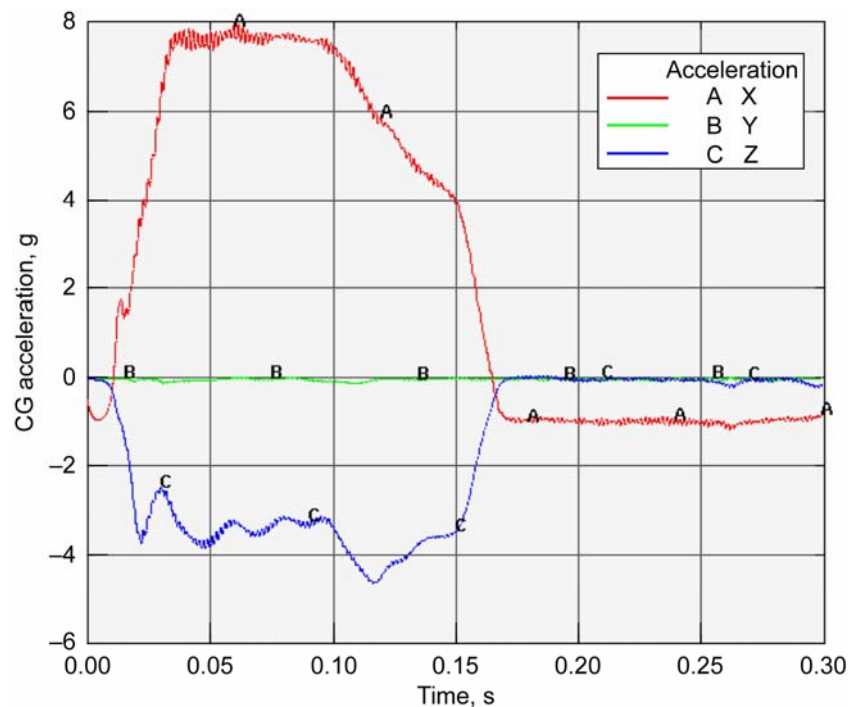


Figure 10.—CEV acceleration. (Vertical velocity = 25 fps, pitch = 0 degrees, horizontal velocity = 20 fps).



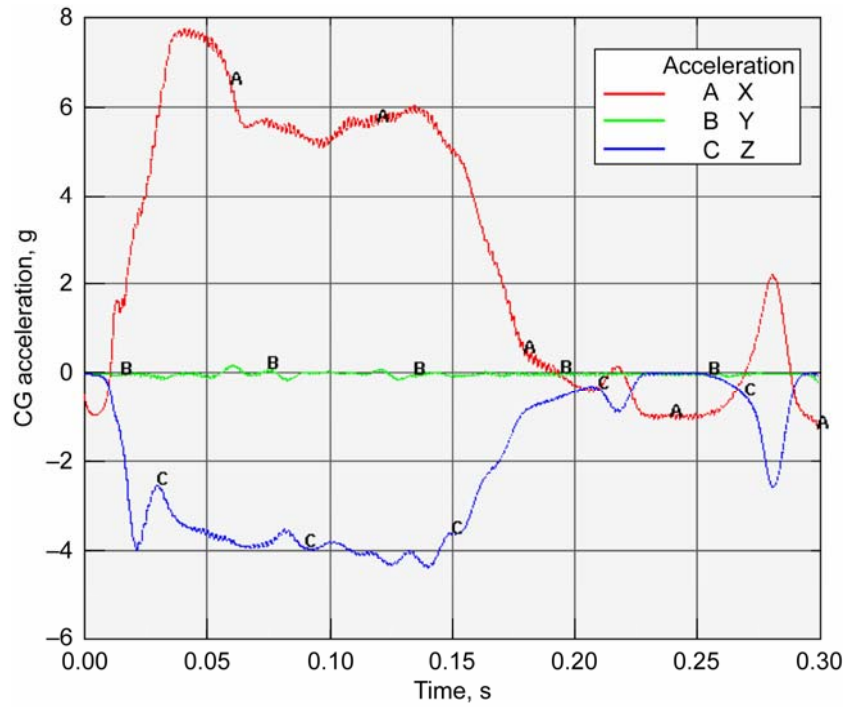


Figure 11.—CEV acceleration. (Vertical velocity = 25 fps, pitch = 0 degrees, horizontal velocity = 40 fps).

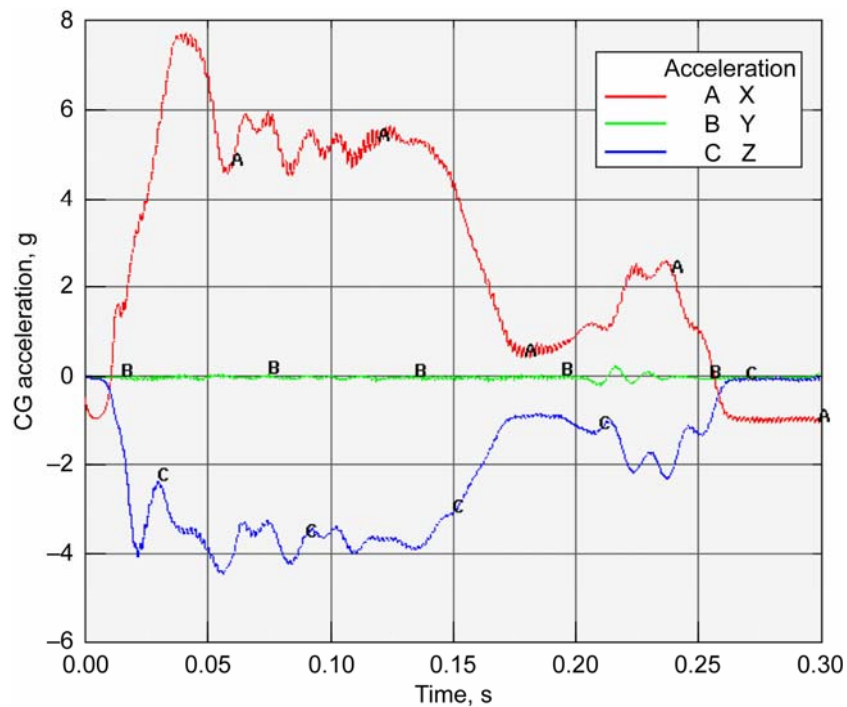


Figure 12.—CEV acceleration. (Vertical velocity = 25 fps, pitch = 0 degrees, horizontal velocity = 60 fps).

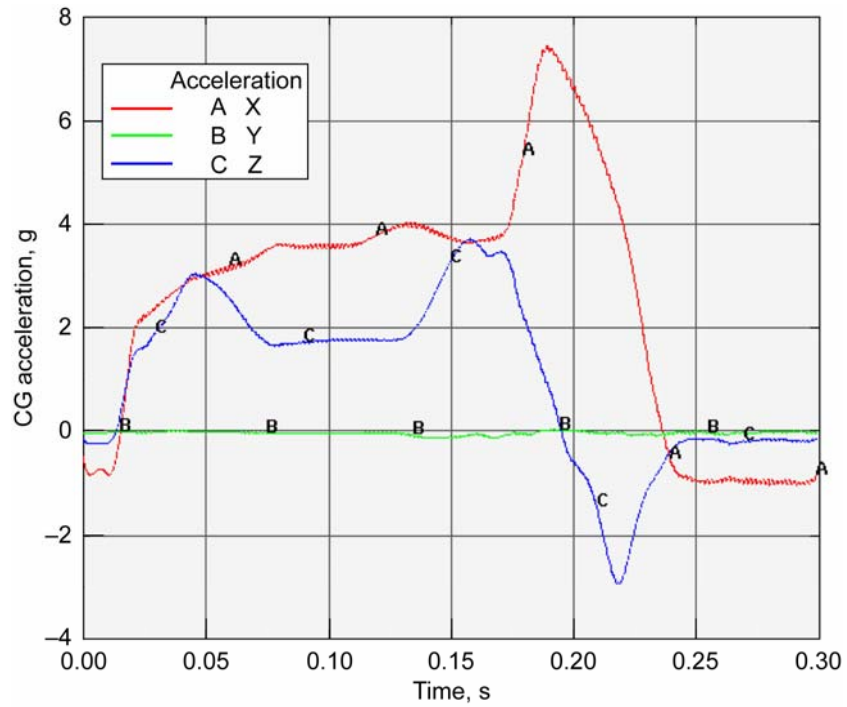


Figure 13.—CEV acceleration. (Vertical velocity = 25 fps, pitch = +15 degrees, horizontal velocity = 0 fps).

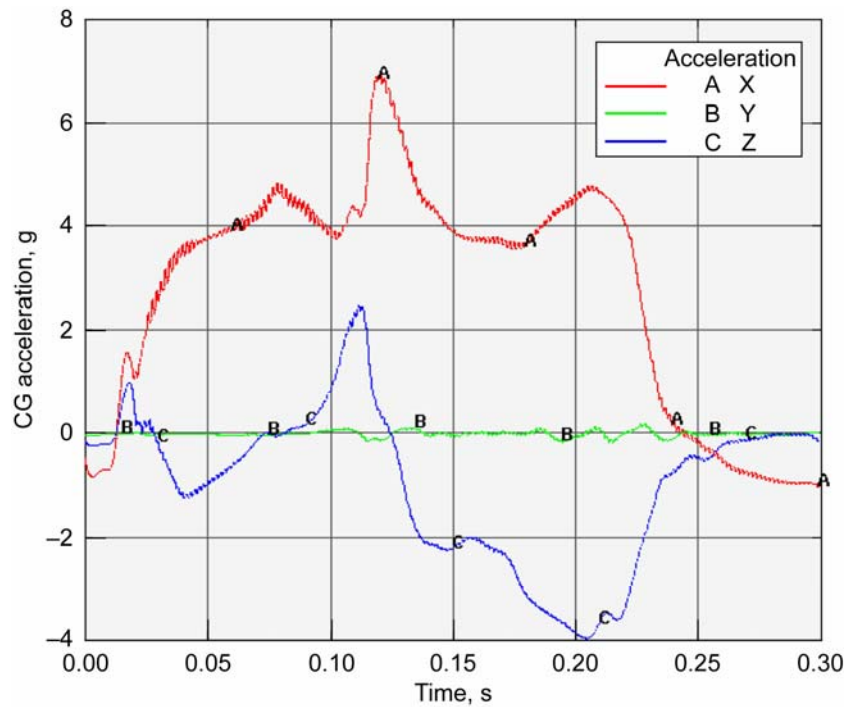


Figure 14.—CEV acceleration. (Vertical velocity = 25 fps, pitch = +15 degrees, horizontal velocity = 20 fps).



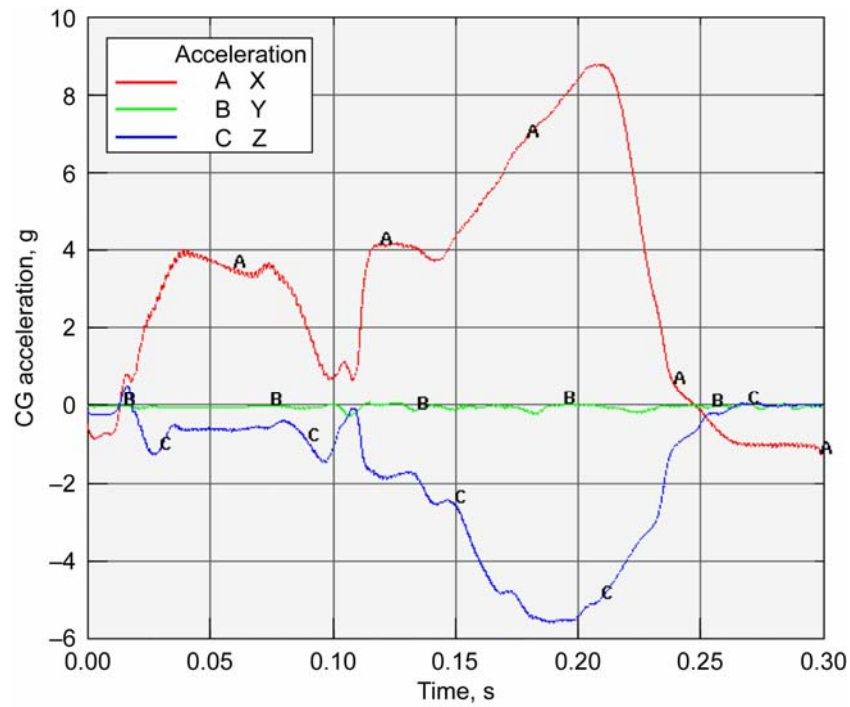


Figure 15.—CEV acceleration. (Vertical velocity = 25 fps, pitch = +15 degrees, horizontal velocity = 40 fps).

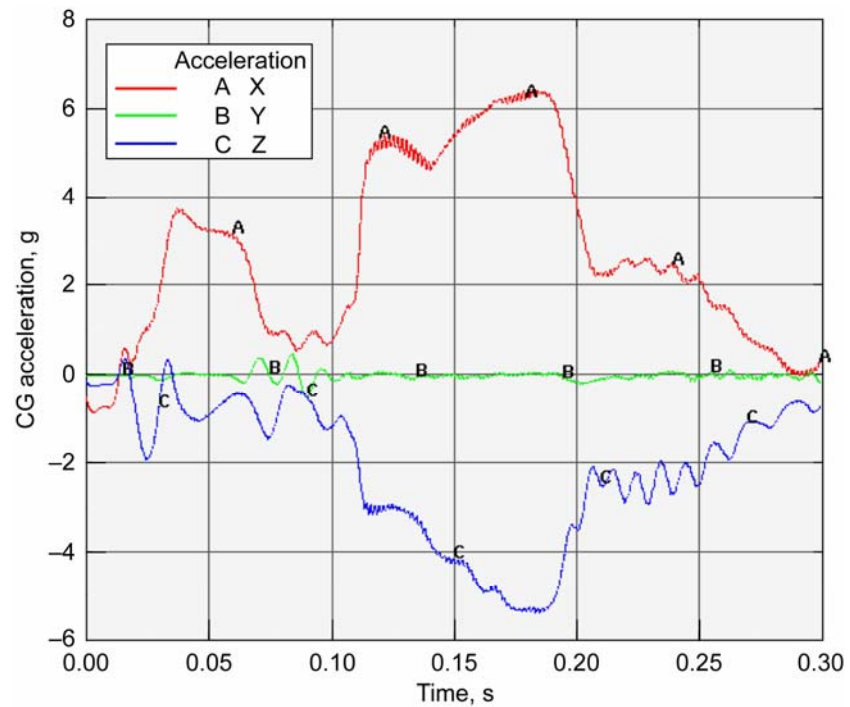


Figure 16.—CEV acceleration. (Vertical velocity = 25 fps, pitch = +15 degrees, horizontal velocity = 60 fps).

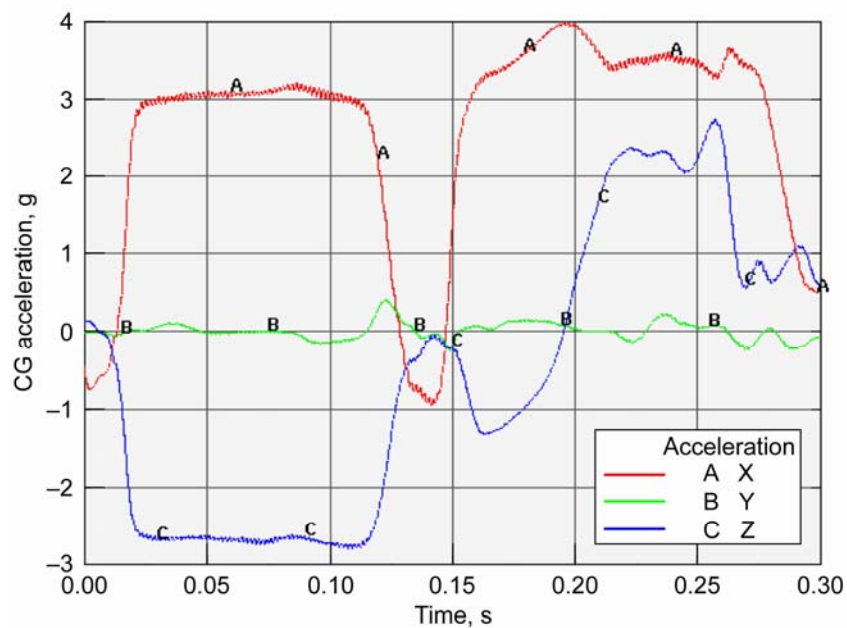


Figure 17.—CEV acceleration. (Vertical velocity = 25 fps, pitch = -15 degrees, horizontal velocity = 0 fps).

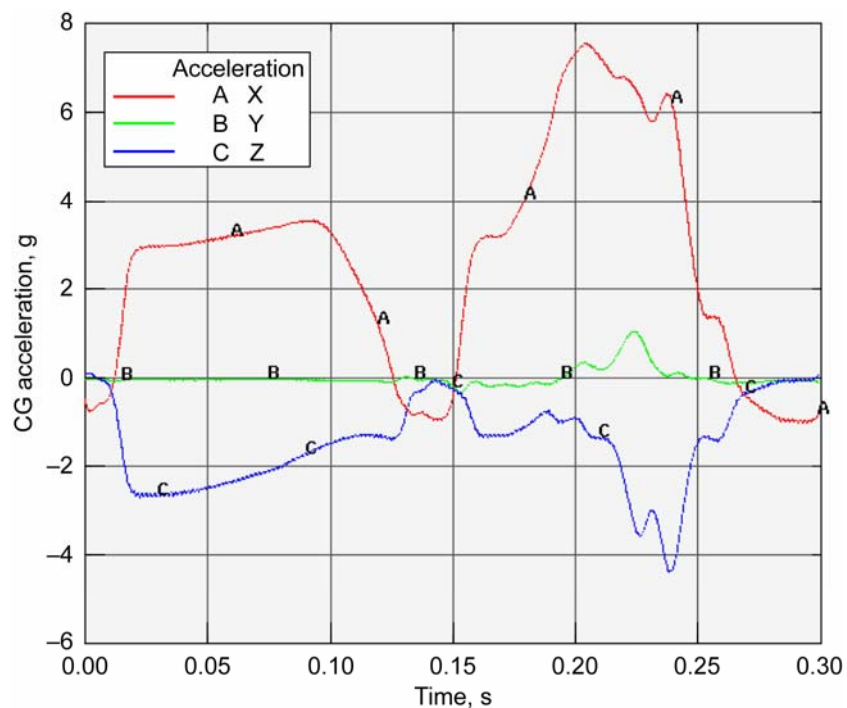


Figure 18.—CEV acceleration. (Vertical velocity = 25 fps, pitch = -15 degrees, horizontal velocity = 20 fps).

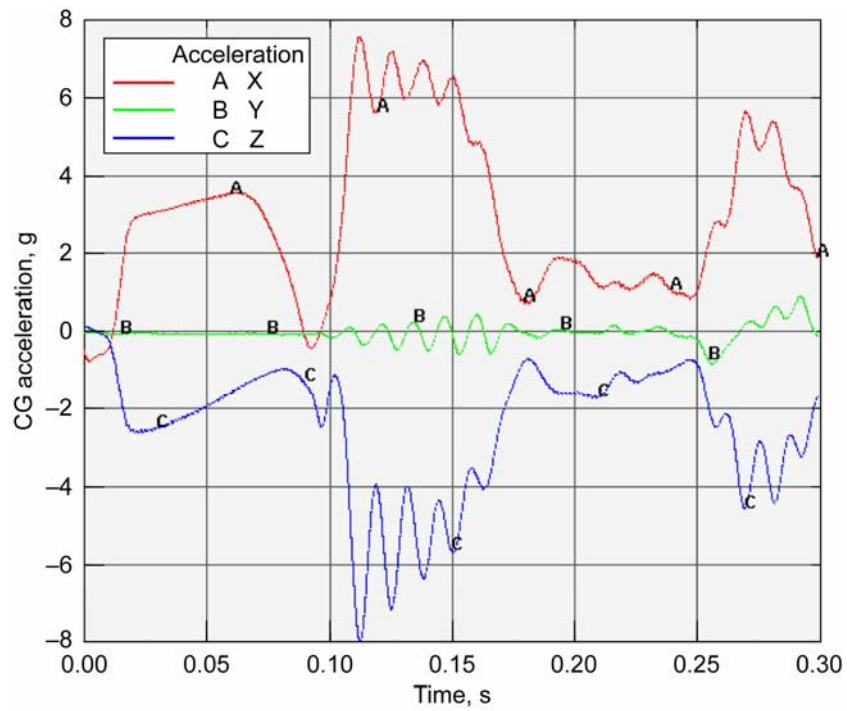


Figure 19.—CEV acceleration. (Vertical velocity = 25 fps, pitch = -15 degrees, horizontal velocity = 40 fps).

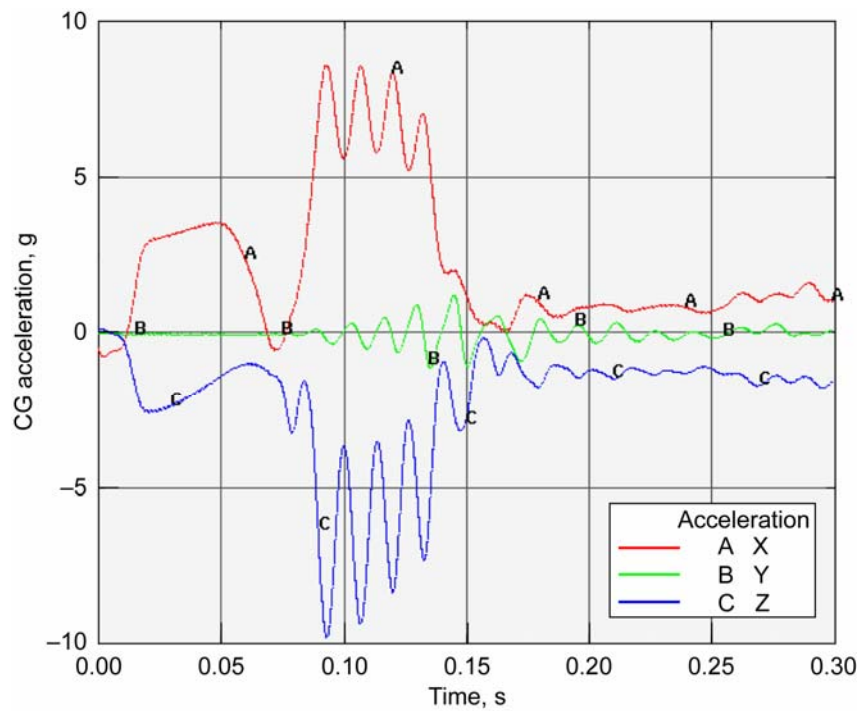


Figure 20.—CEV acceleration. (Vertical velocity = 25 fps, pitch = -15 degrees, horizontal velocity = 60 fps).

## Alternate Leg Configuration

To assess the influence of the deployable leg positioning, a model is created that positioned the legs 90° apart from each other (fig. 21). The original leg positioning is dictated by mechanical constraints and the location of the Crew Module pressure vessel stiffeners. More recent design configurations of the Crew Module eliminate some of these constraints so the deployable legs can be repositioned to an alternate configuration. For this configuration the legs are all equally spaced around the circumference of the vehicle with each leg positioned 90° apart from its adjacent legs. It is believed that this configuration would be optimal for purely vertical landings and less than optimal for landings with larger horizontal landing velocities.

The results for a vertical and horizontal landing velocity of 25 fps and 0 fps, respectively, show a very small reduction in the peak accelerations from the original leg position (fig. 22). While the maximum acceleration for the original leg position is slightly above 9g, the maximum acceleration for the 90° leg position is slightly below 9g. It should be noted that the leg structural properties are taken from the 45/135° configuration and are not redesigned for the new leg positions. Further reductions in the acceleration levels can be expected with a design better optimized for the new leg positions. When the horizontal landing velocity is increased to 60 fps the maximum acceleration decreases from close to 8g down to 6g for the initial portion of the landing. The vehicle then bottoms out, with the pressure vessel hitting the ground, and the acceleration levels become very large. This response is expected since the front legs are positioned more aft of the vehicle than in the original design and are therefore not positioned as well to carry horizontal landing loads.

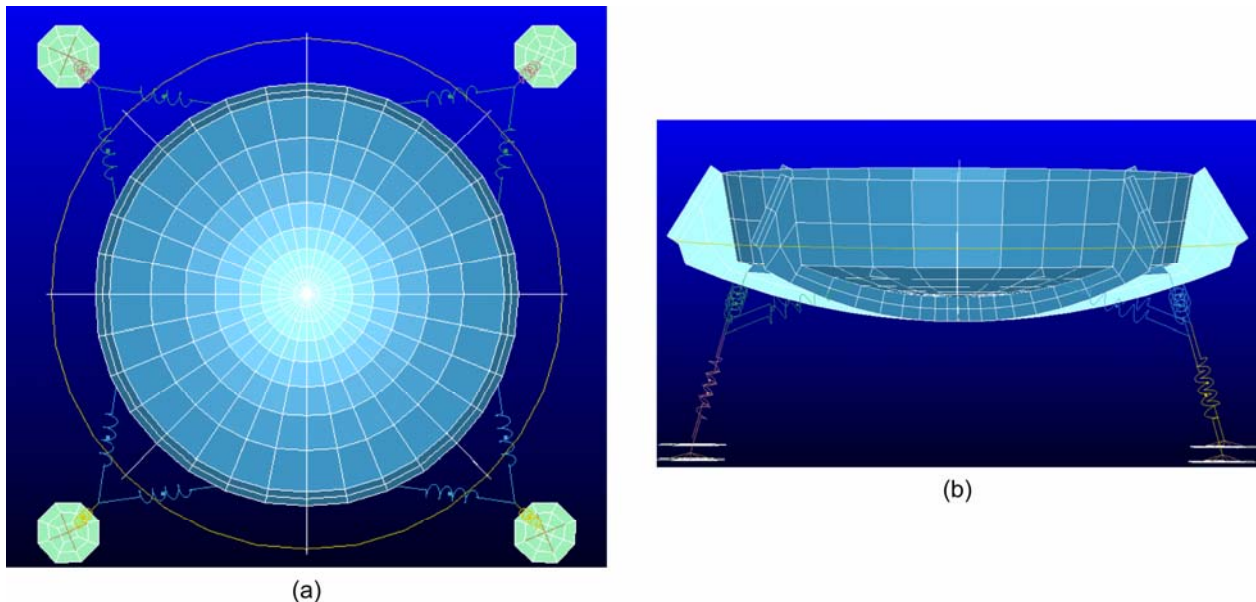


Figure 21.—Deployable legs configured 90 degrees apart. (a) Top view. (b) Side view.

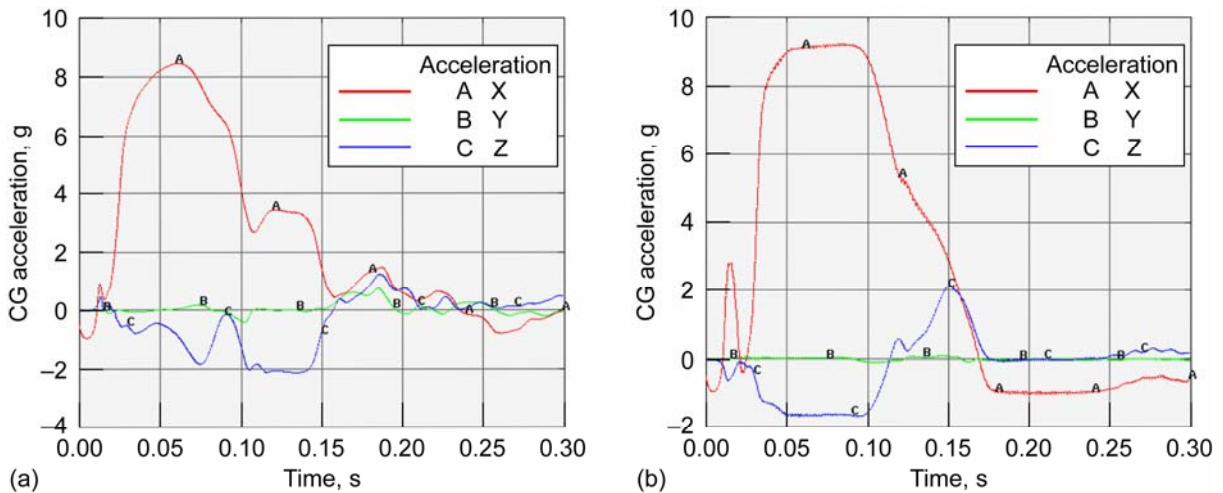


Figure 22.—Comparison between (a) 90 degree leg positioning and (b) original leg positioning. (Vertical velocity = 25 fps, pitch = 0 degrees, horizontal velocity = 0 fps).

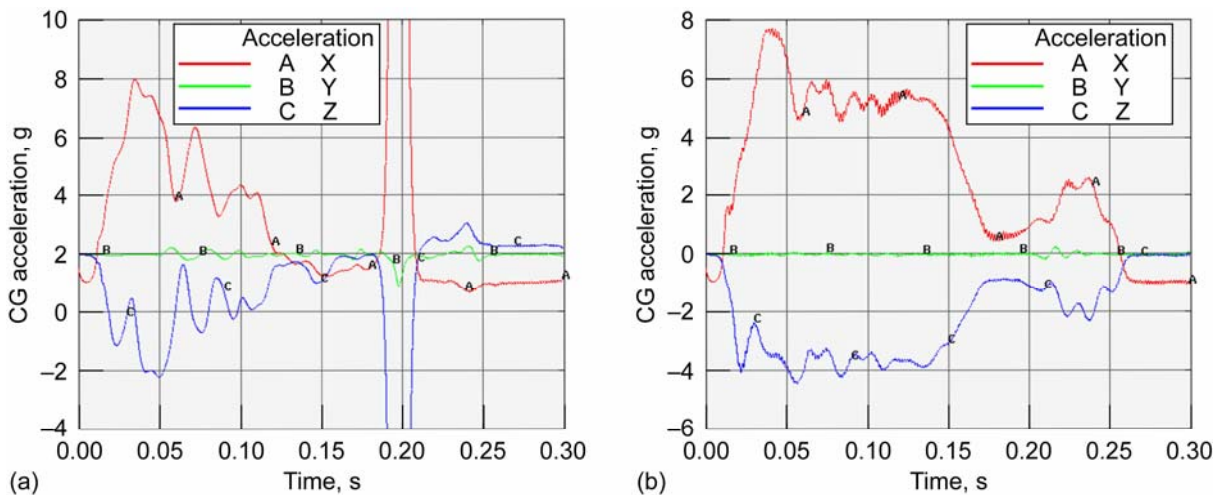


Figure 23.—Comparison between (a) 90 degree leg positioning and (b) original leg positioning. (Vertical velocity = 25 fps, pitch = 0 degrees, horizontal velocity = 60 fps).

## Concluding Remarks

The deployable leg landing attenuation concept is shown to be effective for limiting landing acceleration levels to within acceptable levels. While the present study assessed structural performance, additional work is required to determine the actual weight, reliability, and mechanical design of the deployment system. Furthermore, design work is required to ensure that the structural performance used for the present study can be attained with actual hardware.

It is beyond the scope of the present study to compare the deployable leg concept to other landing attenuation systems under consideration. However it should be pointed out that the present concept is probably most sensitive to the landing surface irregularities. Retro-rockets are probably least sensitive to variations in the landing surface such as ruts or rocks since the rockets, by design, slow the vehicle before contact with the landing surface occurs. Airbags and crushable material, although more sensitive to the landing surface than retro-rockets, can accommodate some surface irregularities since the air bag or crushable surface is spread out under the vehicle. Deployable legs are probably the most sensitive to

landing surface irregularities since the landing leg feet are limited in surface area and thus pose a greater risk to getting “stuck” in holes or making dangerous contact with surface protrusions.

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14. ABSTRACT The NASA Exploration program is investigating the merits of land landing concepts for the Crew Exploration Vehicle (CEV). Four options are under investigation: retro-rockets which fire and slow the vehicle before contact with the landing surface, deployable crushable material which deploys just before landing and crushes during land contact, airbags which deploy just before landing and deflate during land contact, and deployable legs which deploy before landing and contain material that absorbs energy during land contact. The purpose of the present work is to determine the effectiveness of the deployable leg concept. To accomplish this goal, structural models of the deployable leg concept are integrated with the Crew Model (CM) and computational simulations are performed to determine vehicle and component loadings and acceleration levels. Details of the modeling approach, deployable leg design, and resulting accelerations are provided.				
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